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HIGHWAY TRANSPORTATION AGENCY
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A STUDY OF FLEXURAL STRENGTH VS. INDIRECT TENSILE STRENGTH (TENSILE SPLITTING) OF CONCRETE

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Mr. J. C. Womack
State Highway Engineer
California Division of Highways
Sacramento, California

Dear Mr. Womack:

Submitted for your consideration is a report entitled

A Study of

Flexural Strength versus Indirect

Tensile Strength (Tensile Splitting) of Concrete

Study made by . . . . Concrete Section
Under general direction of . . . . D. L. Spellman
Work supervised by . . . . W. H. Ames and J. H. Woodstrom
Report prepared by . . . . B. F. Neal

Yours very truly,

JOHN L. BEATON
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BFN:fp

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FLEXURAL STRENGTH VERSUS INDIRECT TENSILE STRENGTH (TENSILE SPLITTING) OF CONCRETE

ABSTRACT

This report discusses flexural strength tests versus indirect tensile strengths of concrete specimens. Because of the safety hazards and inconveniences connected with the current flexural beam field test procedure, an investigation was made of the tensile splitting test as a possible field control test. Tests were also made to compare the present beam breaker (with a 30-inch span) to a new laboratory developed beam breaker utilizing an 18-inch span.

Details are presented of preliminary testing as well as of a statistically designed program. Results indicate that the tensile splitting test would not be an acceptable replacement for the current field test. However, it was concluded that the new, more easily operated beam breaker utilizing a shorter test specimen would be more desirable than the present beam breaker from the standpoints of safety and convenience.

Key words: Concretes, Concrete testing, Flexural Strength, Modulus of Rupture, Splitting Tensile Strength, Statistical Analysis, Testing Equipment, Laboratory Tests and Field Tests

A STUDY OF FLEXURAL STRENGTH VERSUS INDIRECT TENSILE STRENGTH (TENSILE SPLITTING) OF CONCRETE

Introduction

The modulus of rupture or flexural strength as calculated from concrete beam breaks has, for about 40 years, been the accepted criterion for determining the time at which a portland cement concrete pavement may be opened to traffic. The development of equipment suitable for determining flexural strength in the field provided the engineer with an effective means of determining when the concrete had reached the desired strength and eliminated the need and expense of sending compressive strength cylinders to a central laboratory for quality control tests.

The field beam breaker presently being used in California was developed and put into service in 1930, and has undergone only minor modifications since that time. Positioning of the beam in the testing apparatus requires awkward maneuvering by the person or persons doing the testing and has resulted in numerous lost time injuries. The purpose of this study was to explore better means of field testing in an attempt to eliminate some of the disadvantages that exist.

The 6x6x34-inch mold with steel sides and ends and wooden base plate now commonly used, weighs a total of 94 pounds. Over 100 pounds of concrete is required to fabricate each beam specimen. Because of their weight and shape of the specimens, the moving and transporting of these specimens involves a significant safety hazard.

The safety hazards and inconveniences connected with current methods of fabrication and testing of beams dictates the need for improvement or replacement of the test. In 1963, a State-financed research project was initiated to study tensile splitting as a possible replacement for the current flexure beam test. Later in the study when the shortcomings of the tensile splitting test became known, effort was directed toward improvement of the flexural strength test by using a smaller, lighter weight specimen, and by redesign of the beam breaker apparatus.

Conclusions

The results of this study indicate that the tensile splitting test, as employed in this study, is not an acceptable replacement for the flexural beam test currently being used in the field. The large variations which occur when using the hand-operated tensile splitting device tends to lower confidence in the test, considerably reducing the value of this method as a control test.

A flexure beam testing apparatus developed in this laboratory using a 20-inch specimen with an 18-inch span and center-point loading appears to be the most satisfactory of the alternatives considered for field control testing. Flexural strengths obtained by this method are comparable to those obtained using the current test procedure which utilizes a 30-inch span with center-point loading. The improved safety features of lighter weight specimens and a more convenient testing device should make the method readily acceptable to field personnel.

Methods and Equipment

In searching for a replacement for the beam test, the following factors were considered:

1. The test must provide reliable results to be used for quality control and as the criterion for opening of pavement to traffic.
2. Hazards to safety of operating personnel must be reduced.
3. The test method and equipment must be suitable for field use. The equipment should be portable, easily maintained and rugged enough to withstand normal field abuse.
4. The test must be economically feasible.

In recent years, several researchers[1]* have reported results of investigations of the tensile splitting strength of concrete. Narrow and Ullberg[2] reported that a consistent relationship exists between flexural strength and tensile splitting strength. On the basis of these published reports, it appeared that this indirect tensile test could adequately meet the requirements for a replacement of the flexure type test.

There was no record of the tensile splitting test ever having been performed using equipment other than laboratory compression testing machines. In order to comply with the project requirements, it was necessary to design and build a portable testing machine suitable for field use (see photographs). With this device, the load is transmitted to the test specimen by suitable bearing surfaces attached to the loading frame. Force is applied by a 20-ton capacity hydraulic jacking system. The ultimate vertical load is obtained by multiplying the line pressure gage reading at failure by a gage factor. The tensile splitting strength is calculated as follows:

$$T = \frac{2P}{\pi l d}$$

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*Numbers refer to references at the end of this report.

Where T = tensile splitting strength in psi
P = maximum applied vertical load in lbs.
l = length of cylinder in inches
d = diameter of cylinder in inches

In addition to the tensile splitting tests, a limited study was made of a lighter weight, more compact model beam breaking apparatus as shown in Photos 3, 4, and 5. This device also fabricated at this laboratory, was designed to accomodate test beams 20 inches in length instead of the current 34-inch length. While a 34-inch long test beam weighs approximately 105 lbs., a 20-inch long beam weighs only about 65 lbs. The test beam, besides being lighter in weight, is easily set into position on this apparatus, thereby eliminating some of the safety hazard inherent in our present method of testing.

Discussion

Preliminary Tests

The first tests were made on the hydraulic compression testing machine to familiarize personnel with the tensile splitting procedure. To assure uniform bearing along the center line of the cylinders, plywood strips, as recommended in ASTM procedures, were positioned between the testing machine platens and the specimen. Results as shown in Table 1, indicated some degree of correlation. When using the plywood bearing strips, it was noted that many of the strips had knots or missing laminations that might result in non-uniform bearing and erroneous answers.

In an attempt to improve the uniformity of the bearing, rubberized fabric strips were used for the first series of tests with the hand-operated device. The results of these tests are shown in Table 2. The variation coefficients were somewhat higher for the tensile splitting strengths than for the flexural strengths, but the results were encouraging enough to warrant continuation of the testing.

Table 3 lists the results of a few tests in which the cylinders were split with steel bearing strips with the contact edges rounded to a 1/8-inch radius. Test results were very erratic and average strengths were lower than those obtained with other types of bearing materials, probably due to localized loads on aggregate near the contact surface.

In order to provide a better statistical comparison of equipment and bearing surfaces, a special series of tests was made to compare several types of bearing strips. The results of these tests are shown in Table 4. From these results, it was apparent that steel knife edges and the balsa wood bearing strips were not satisfactory. Considerable improvement in the variation coefficients was shown in tests using rubberized fabric bearing strips.

Field tests to compare tensile splitting strengths with flexural strengths are reported in Table 5. These tests were performed on the job by District Construction personnel using their own beam breaking device and the laboratory's tensile splitting apparatus. The results of these tests show the coefficient of variation values for the tensile splitting tests to be considerably higher than those for the flexural tests.

Tables 6 and 7 show comparisons of one and two beam breaks to sets of three and six tensile tests with different variables. The variables include age, maximum size of aggregate, cement factor, and breaking devices. Hardboard bearing strips were used for all these tests. Results show within-batch and between-batch variations as well as variations between hand-operated breakers and the hydraulic press. The ratio of tensile to flexural strength varies considerably with the different strength levels obtained and with the different breaking devices. The lack of sufficient data to permit a satisfactory statistical analysis led to the planning of another test program based on statistical concepts.

One series of tests was made to compare flexural strengths with those of tensile splitting strengths of cores taken from hardened concrete. One core was taken from each broken beam end and tested on the same day as the beam. The results as shown in Table 8, indicate some degree of correlation.

Statistical Program

With aid from the Highway Division's Statistical Methods Development Unit, a testing program based on statistical concepts was designed. The planned program was as follows:

A. Five methods of testing were to be evaluated.

1. Flexural test with 6x6x34-inch specimens using a 30-inch span and standard field beam breaker with center-point loading.

2. Flexural test with 6x6x20-inch specimens using an 18-inch span and the smaller laboratory-developed beam breaker with center-point loading.

3. Tensile splitting test with 6x6-inch cylindrical specimens using the laboratory-developed, hand-operated splitter.

4. Tensile splitting test with 6x6-inch cylindrical specimens using the laboratory hydraulic press.

5. Tensile splitting test with 6-inch diameter by 12-inch long cylindrical specimens using the hydraulic press.

B. Three cement factors were included - 4.5, 5.5, and 6.5 sacks per cubic yard. All specimens for a given cement factor were to be fabricated from a single truckload of concrete.

C. Two rounds were to be tested for each cement factor.

D. The first, middle, and last portions of each transit-mix truckload were to be tested separately.

E. Five specimens were to be fabricated for each test method from each portion of the truckload.

F. Curing was to be uniform. (The method used was to place the fabricated specimens in a damp, shaded area and cover with plastic sheeting.)

G. Bearing strips for the tensile splitting tests were to be plywood, 1/8 x 1-inch x 7 or 13 inches, and individually inspected for uniformity.

H. The test age for all specimens was 7 days.

With the exception of controlled cement factor, the program was executed as outlined. The strength results from Round 2 were not in agreement with those from Round 1. Since the strengths obtained from Round 1 were in the expected range, it is assumed that the cement factors of Round 1 were close to the planned design and errors were made in the concrete batching for Round 2. The test specimens from Round 1 had already been discarded, but chemical cement factor tests were made on samples of hardened concrete from each truckload of Round 2. These tests indicated that instead of a cement factor range of from 4.5 to 6.5 sacks, the range was from 4.5 to 5.0 sacks per cubic yard. (The calculations of cement content on hardened concrete are considered accurate only to a plus or minus one-half sack.) As a result of the wrong levels of cement content, there were no duplications of the high and low strengths of Round 1. The average strength results of these tests, standard deviations, and coefficients of variation are shown in Tables 9 through 13. Since the exact cement factors are unknown, those shown in the tables are the planned normal range of 4.5, 5.5, and 6.5 sacks per cubic yard. In any event, a sufficient range of strength was achieved.

Analysis of variance tests were made separately on the flexural strengths and the tensile strengths. The only information of particular value which was found by this test, was that the portion of the truckload tested was not a significant variable. This fact permitted the averaging of all 15 specimens for each test rather than just 5. The results of this grouping, as well as the over-all averages for the coefficients of variation, are summarized in Table 14.

The coefficient of variation is a measure of dispersion about the average in which the variability of a set of numbers is expressed on a relative scale rather than on an absolute scale. Since the values for tensile splitting strength are only about one-half to two-thirds of the flexural strength, the relative variations appear more meaningful. It can be seen in Table 14 that considerable variations occur, regardless of the test method involved. Although test methods 4 and 5 indicate the least amount of variations, they involve the use of a laboratory hydraulic press and would not be practical for field tests. The two flexural test methods compared are approximately equal in variability, although the method utilizing 20-inch beams with an 18-inch span gives strength results slightly higher than the standard 34-inch beam test which utilizes a 30-inch span. From a statistical standpoint, the tensile test performed with the laboratory-developed breaker would provide results as reliable as the flexural test, provided two or more tensile tests were averaged to give a single test result. However, from a practical standpoint, the wide variations in results create a lack of confidence in the test and would, in effect, reduce the value of this method for control testing.

Photographs 1 through 9 show portions of each of the five test methods evaluated in this program.

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Table 1

Tensile Splitting Strengths vs. Flexural Strengths
(Hydraulic Press for Both)

Aggregate Source	Age, Days	Tensile Splitting Tests: Sample Size n	Tensile Splitting Tests: Mean, PSI $\overline{X}$	Tensile Splitting Tests: Std. Dev. PSI S	Tensile Splitting Tests: Coeff. of Variation, Percent V	Flexural Tests: n	Flexural Tests: $\overline{X}$	Flexural Tests: S	Flexural Tests: V
5.0-sack									
Fair Oaks	10	5	364	26	7.1	3	605	48	7.9
" "	14	10	328	43	13.1	5	567	25	4.4
" "	14	10	325	50	15.4	5	509	32	6.3
5.5-sack									
Fair Oaks	28	5	446	37	8.3	3	660	58	8.8
Cuddy Cr.	14	10	334	34	10.2	5	539	17	3.2
Lodi	14	4	375	25	6.7	4	565	31	5.5
Lodi (AE)	14	4	335	31	9.3	4	545	29	5.3
6.0-sack									
Cuddy Cr.	14	9	381	37	9.7	5	550	57	10.4
Cuddy Cr. (AE)	14	10	339	41	12.1	5	517	78	15.1
Lodi	14	8	350	52	14.9	8	510	60	11.8
Lodi (AE)	14	8	295	26	8.8	8	480	58	12.1
Fair Oaks	14	4	445	12	2.7				
" "	14	4	465	54	11.6				
Fair Oaks (AE)	14	4	480	29	6.0				
Average Coefficient of Variation					10.2				8.9

Note: Beams - 6x6x20-inch; third point loading
Cylinders - 6x6-inch; plywood bearing strips, 1/4x3/4x7-inch
Aggregate - 1-1/2-inch maximum size

Table 2

Tensile Splitting Strengths vs. Flexural Strengths
(Hand operated tensile splitting apparatus for cylinders, hydraulic press for beams)

Aggregate Source	Days	Tensile Splitting Tests				Flexural Tests			
		n	$\bar{X}$	S	V	n	$\bar{X}$	S	V
5.0-sack									
Fair Oaks	14	10	296	31	10.5	5	545	39	7.2
Irwindale	14	10	295	34	11.5	5	570	35	6.1
Fair Oaks	14	10	301	38	12.6	5	555	59	10.6
Fresno	14	10	307	53	17.3	5	555	30	5.4
Fair Oaks	14	10	323	33	10.2	5	595	36	6.1
Castaic	14	10	319	35	11.0	5	570	35	6.1
Fair Oaks	14	9	281	35	12.5	2	565		
" "	14	9	342	42	12.3	5	575	36	6.3
Atascadero	14	10	317	16	5.0	5	520	9	1.7
Fair Oaks	14	10	285	46	16.1	5	470	36	7.7
Mission Vly.	14	10	290	50	17.2	5	470	75	16.0
Fair Oaks	14	10	356	30	8.4	5	575	58	10.1
Merced	14	10	335	50	14.9	5	625	39	6.2
Fair Oaks	14	10	307	42	13.7	5	515	51	9.9
Centerville	14	10	376	45	12.0	5	560	73	13.0
Fair Oaks	14	10	326	37	11.3	5	585	35	6.0
Mt. Shasta	14	10	352	47	13.4	5	635	31	4.9
Fair Oaks	14	10	344	28	8.1	4	575	69	12.0
Little Rock	14	10	308	45	14.6	4	535	53	9.9
Fair Oaks	10	9	209	24	11.5	2	420		
5.5-sack									
Irwindale	14	10	326	49	15.0	5	610	28	4.6
Fresno	14	10	323	57	17.6	5	630	46	7.3
Castaic	14	10	343	43	12.5	5	610	36	5.9
Atascadero	14	10	355	32	9.0	5	605	46	7.6
Mission Vly.	14	10	330	58	17.6	5	645	66	10.2
Merced	14	10	393	32	8.1	5	670	68	10.1
Centerville	14	10	378	44	11.6	5	610	73	12.0
Mt. Shasta	14	10	372	38	10.2	5	680	40	5.9
Little Rock	14	10	311	42	13.5	4	545	9	1.7

Continued on page 2

Aggregate Source	Days	Tensile Splitting Tests				Flexural Tests			
		n	$\overline{X}$	S	V	n	$\overline{X}$	S	V
6.0-sack									
Fair Oaks (AE)	10	9	344	42	12.2	2	590		
Fresno	14	10	349	57	16.3	5	625	91	14.6
Castaic	14	10	371	56	15.1	5	660	48	7.3
Fair Oaks	14	9	351	37	10.5	2	665		
Lodi	14	6	310	87	28.1	2	625		
"	14	6	350	38	10.9	2	600		
Atascadero	14	10	388	25	6.4	5	620	64	10.3
Mission Vly	14	10	330	63	19.1	5	670	125	18.6
Merced	14	10	423	31	7.3	5	725	65	9.0
Centerville	14	10	405	36	8.9	5	650	65	10.0
Mt. Shasta	14	10	384	34	8.8	5	750	50	6.7
Little Rock	14	10	325	38	11.7	4	590	34	5.7
Average Coefficient of Variation					12.8				9.2

Note: Beams - 6x6x20-inch; third point loading
Cylinders - 6x6-inch; rubberized fabric bearing pad, 5/16 x 1/2 x 7 inches
Aggregate - 1-1/2-inch maximum size

Table 3

Tensile Splitting Strengths vs. Flexural Strengths
(Hand operated tensile splitting apparatus for cylinders; hydraulic press for beams)

Aggregate Source	Age, Days	Tensile Splitting Tests				Flexural Tests			
		n	$\bar{X}$	S	V	n	$\bar{X}$	S	V
<u>5.0-sack</u>									
Fair Oaks	14	9	206	48	23.3	4	590	62	10.5
Rialto	14	10	226	43	19.0	5	600	61	10.2
Fair Oaks	14	4	220	76	34.5				
E. of Los Banos	14	10	185	45	24.3				
Fair Oaks	14	7	220	28	12.7				
<u>5.5-sack</u>									
Rialto	14	10	256	26	10.2	5	665	32	4.8
E. of Los Banos	14	10	194	53	27.3				
<u>6.0-sack</u>									
Rialto	14	10	263	42	16.0	5	705	61	8.7
E. of Los Banos	14	10	197	45	22.8				
Average Coefficient of Variation					21.5				8.6

Note: Beams - 6x6x20-inch; third point loading
Cylinders - 6x6-inch; knife edge bearing strips with 1/8-inch radius
Aggregate - 1-1/2-inch maximum size

Table 4

Tensile Splitting Strengths with Different Bearing Surfaces and Equipment
(4 consecutive specimens and total for each series)

Equipment	Bearing Surface	Age	n	$\bar{X}$	S	V
Hydraulic Press	Steel knife edge	10	4	246	20	8.1
			4	279	17	6.1
			4	298	23	7.7
			4	282	8	2.8
			16	276	25	9.1
Tensile splitting device Hand operated	Steel knife edge	10	4	289	46	15.9
			4	244	42	17.2
			4	202	17	8.4
			4	220	31	14.1
			16	239	46	19.2
Hydraulic press	Fabric	10	4	368	21	5.7
			4	343	21	6.1
			4	409	22	5.4
			4	362	39	10.8
			16	370	34	9.2
Tensile splitting device Hand operated	Fabric	10	4	377	20	5.3
			4	396	24	6.1
			4	363	16	4.4
			4	394	10	2.5
			16	383	22	5.7
Hydraulic Press	Steel knife edge	7	4	251	31	12.4
			4	212	10	4.7
			4	246	6	2.4
			3	247	49	19.8
			15	238	29	12.2
Tensile splitting device Hand operated	Steel knife edge	7	4	170	28	16.5
			4	177	38	21.5
			4	188	72	38.3
			4	188	7	3.7
			16	181	38	21.0
Hydraulic Press	Balsa Wood (1/8" square)	7	4	248	16	6.5
			4	248	16	6.5
			4	280	46	16.4
			4	276	33	12.0
			16	263	32	12.2
Tensile splitting device Hand operated	Balsa Wood	7	4	260	28	10.8
			4	228	47	20.6
			4	266	50	18.8
			4	252	15	6.0
			16	252	37	14.7

Note: Aggregate - 1-1/2 inch maximum size from American River near Fair Oaks
Concrete contained 5.0 sacks of cement per cubic yard.

Table 5

Tensile Splitting Strengths vs. Flexural Strength
(Field tests using hand-operated tensile
splitting device and standard field
beam breaker)

Aggregate Source	Age	Tensile Tests				Flexural Tests			
		n	$\overline{X}$	S	V	n	$\overline{X}$	S	V
Mt. Shasta 6-sk., AE	7	6	255	34	13.2	3	525	19	3.5
	7	6	250	24	9.4	3	525	63	12.1
	7	6	240	31	12.9	3	590	24	4.0
	7	6	230	22	9.6	3	500	16	3.1
	7	6	235	28	11.7	1	625		
	7	6	250	31	12.3	3	615	12	1.9
	7	6	260	37	14.0	3	595	27	4.6
	7	6	260	20	7.5	2	555		
	7	6	300	25	8.3	3	650	24	3.6
	7	6	265	44	16.5	1	540		
Average			255				575		
Average Coefficient of Variation					11.8				5.4

Note: Beams 6x6x34-inch; center-point loading
Cylinders 6x6-inch; rubberized fabric bearing pad 5/16x1/2x7-inch

Aggregate - 1-1/2-inch maximum size

Table 6

Tensile Splitting Strengths vs. Flexural Strengths
(Hydraulic Press for Both)

	Age, Days	Tensile Tests			Flexural Tests		
		n	X	$\overline{X}$	n	X	$\overline{X}$
5-sack 1-1/2" max.	3	3	171 203 198	191	1	320	
		3	182 155 177	171	1	355	
Average		6		181	2		338
	7	3	267 218 298	261	1	500	
		3	299 265 293	286	1	435	
Average		6		273	2		468
6-sack, 1-1/2" max.	3	3	256 283 301	280	1	480	
		3	263 261 293	272	1	470	
Average		6		276	2		475
	7	3	300 387 368	352	1	660	
		3	353 389 238	327	1	660	
Average		6		339	2		660

Continued on Page 2

	Age, Days	Tensile Tests			Flexural Tests		
		n	X	$\bar{X}$	n	X	$\bar{X}$
6-sack 3/8" Max.	3	3	249 225 205	226	1	405	
		3	191 259 230	227	1	405	
Average		6		227	2		405
	7	3	362 341 334	346	1	545	
		3	315 285 334	311	1	450	
Average		6		329	2		498

Note: Beams - 6x6x20-inch broken by third point loading
Cylinders - 6x6 - inch, hardboard bearing strips, 1/8x1x7-inches
Aggregates - from Sacramento River near Fair Oaks

Table 7

Tensile Splitting Strengths vs. Flexural Strengths
(Hand-operated tensile splitting device and
18-inch span field beam breaker.)

	Age, days	Tensile Tests			Flexural Tests		
		n	X	$\bar{X}$	n	X	$\bar{X}$
5-sack, 1-1/2" max.	3	3	95				
			179	136	1	385	
			133				
		3	202				
			110	156	1	300	
			156				
Average		6		146	2		343
	7	3	232				
			193	217	1	560	
			225				
		3	194				
			148	204	1	560	
			270				
Average		6		210	2		560
6-sack, 1-1/2" max.	3	3	263				
			179	222	1	605	
			225				
		3	255				
			190	231	1	605	
			248				
Average		6		226	2		605
	7	3	248				
			248	233	1	690	
			202				
		3	206				
			248	267	1	700	
			348				
Average		6		250	2		695

Continued on Page 2

Table 7 (Continued)

	Age Days	Tensile Tests			Flexural Tests		
		n	X	$\overline{X}$	n	X	$\overline{X}$
6-sack, 3/8" max.	3	3	156 156 152	155	1	480	
		3	156 187 221	188	1	470	
Average		6		171	2		475
	7	3	186 209 202	199	1	620	
		3	160 162 251	191	1	615	
Average		6		195	2		618

Note: Beams 6x6x20-inch, broken by center-point loading on new laboratory developed breaker

Cylinders 6x6-inch, hardboard bearing strips, 1/8x1x7-inches

Table 8

Tensile Splitting Strength of Cores
vs. Flexural Strengths
(Hydraulic Press for Both)

Aggregate Source	Age Days	Tensile Tests				Flexural Tests			
		n	$\bar{X}$	S	V	n	$\bar{X}$	S	V
Fair Oaks 5-sack	14	8	401	52	13.0	5	615	69	11.2
Ventura 5-sack	14	10	377	60	15.9	5	560	45	8.0
5-1/2-sk. 2" slump	14	8	356	66	18.5	5	565	59	10.4
4" slump	14	10	348	60	17.2	5	530	24	4.5
6-sack	14	10	426	83	19.5	5	565	45	8.0

Note: Beams - 6x6x20-inch; third point loading

Tensile specimens - 5x6-inch cores; hard board bearing strips 1/8x1/4x7-inches

Cores were taken from each beam end on same day as beam break

Aggregate - 1-1/2-inch maximum size

Table 9

Flexural Strengths by Standard Method
(34-inch beams with 30-inch span
and center-point loading)

Portion of Truck	Nominal C.F.(1)	4.5-sack		5.5-sack		6.5-sack	
	Round	R_1	R_2	R_1	R_2	R_1	R_2
First (n=5)	$\bar{X}$	434	596	627	650	707	636
	S	47	26	75	48	83	34
	V	10.8	4.4	12.0	7.4	11.7	5.3
Middle (n=5)	$\bar{X}$	468	608	561	659	748	563
	S	26	34	27	30	62	50
	V	5.6	5.6	4.8	4.6	8.3	8.9
Last (n=5)	$\bar{X}$	453	594	556	666	700	543
	S	63	21	40	50	45	26
	V	13.9	3.5	7.2	7.5	6.4	4.8
Entire Truck (n=15)	$\bar{\bar{X}}$	452	599	581	658	718	581
	S	47	26	58	41	64	54
	V	10.4	4.3	10.0	6.2	8.9	9.3

(1)"Nominal" cement factor is intended cement factor. Actual cement factor for certain rounds differed.

7-day strengths
Aggregate - 1-1/2-inch maximum size

Table 10

Flexural Strength of 20-inch Beams
(18-inch span with center-point loading)

Portion of Truck	Nominal C.F.(1) Round	4.5-sack R_1	4.5-sack R_2	5.5-sack R_1	5.5-sack R_2	6.5-sack R_1	6.5-sack R_2
First (n=5)	$\bar{X}$	481	636	622	723	821	622
	S	28	66	55	55	91	48
	V	5.8	10.4	8.8	7.6	11.1	7.7
Middle (n=5)	$\bar{X}$	487	594	596	636	838	620
	S	44	31	52	72	91	27
	V	9.0	5.2	8.7	11.3	10.9	4.4
Last (n=5)	$\bar{X}$	452	608	635	638	827	596
	S	48	67	58	67	28	13
	V	10.6	11.0	9.1	10.5	3.4	2.2
Entire truck (n=15)	$\bar{\bar{X}}$	473	612	617	666	829	613
	S	41	56	53	73	71	33
	V	8.7	9.2	8.6	11.0	8.6	5.4

(1)"Nominal" cement factor is intended cement factor. Actual cement factor for certain rounds differed.

7-day strengths
Aggregate - 1-1/2-inch maximum size

Table 11

Tensile Splitting Strengths of 6x6-inch Cylinders
(Hand-operated tensile splitting device)

Portion of Truck	Nominal C.F.[1]	4.5-sack		5.5-sack		6.5-sack	
	Round	R1	R2	R1	R2	R1	R2
First (n=5)	$\bar{X}$	221	298	308	313	392	335
	S	17	34	36	35	28	33
	V	7.7	11.4	11.7	11.2	7.1	9.8
Middle (n=5)	$\bar{X}$	212	308	283	320	355	291
	S	3	52	48	49	17	36
	V	1.4	16.9	17.0	15.3	4.8	12.4
Last (n=5)	$\bar{X}$	208	310	241	339	349	304
	S	11	11	23	22	16	34
	V	5.3	3.5	9.5	6.5	4.6	11.2
Entire Truck (n=15)	$\bar{\bar{X}}$	214	305	277	324	365	310
	S	12	34	45	36	28	37
	V	5.6	11.1	16.2	11.1	7.7	11.9

[1] "Nominal" cement factor is intended cement factor. Actual cement factor for certain rounds differed.

7-day strengths
Aggregate - 1-1/2-inch maximum size

Table 12

Tensile Splitting Strengths of 6x6-inch Cylinders
(Hydraulic press)

Portion of Truck	Nominal C.F.[1] Round	4.5-sack		5.5-sack		6.5-sack	
		R_1	R_2	R_1	R_2	R_1	R_2
First (n=5)	$\bar{X}$	225	323	305	347	434	353
	S	6	15	47	22	26	23
	V	2.7	4.6	15.4	6.3	6.0	6.5
Middle (n=5)	$\bar{X}$	250	317	336	336	410	335
	S	12	19	32	43	23	15
	V	4.8	6.0	9.5	12.8	5.6	4.5
Last (n=5)	$\bar{X}$	230	332	316	362	451	341
	S	21	28	21	24	31	27
	V	9.1	8.4	6.6	6.6	6.9	7.9
Entire truck (n=15)	$\bar{\bar{X}}$	235	324	319	348	432	343
	S	17	27	33	31	30	22
	V	7.2	8.3	10.3	8.9	6.9	6.4

(1) "Nominal" cement factor is intended cement factor. Actual cement factor for certain rounds differed.

7-day strengths
Aggregate = 1-1/2-inch maximum size

Table 13

Tensile Splitting Strengths of 6x12-inch Cylinders
(Hydraulic Press)

Portion of Truck	Nominal C.F.(1) Round	4.5-sack		5.5-sack		6.5-sack	
		R_1	R_2	R_1	R_2	R_1	R_2
First (n=5)	$\bar{X}$	238	299	278	323	397	299
	S	6	16	32	25	12	28
	V	2.5	5.4	11.5	7.7	3.0	9.4
Middle (n=5)	$\bar{X}$	252	286	292	305	393	292
	S	8	10	18	25	13	13
	V	3.2	3.5	6.2	8.2	3.3	4.4
Last (n=5)	$\bar{X}$	233	297	302	358	395	295
	S	9	18	15	30	12	23
	V	3.9	6.1	5.0	8.4	3.0	7.8
Entire truck (n=15)	$\bar{\bar{X}}$	241	294	290	329	395	295
	S	11	15	24	33	11	21
	V	4.6	5.1	8.3	10.0	2.9	7.1

(1) "Nominal" cement factor is intended cement factor. Actual cement factor for certain rounds differed.

7-day strengths
Aggregate - 1-1/2-inch maximum size

Table 14

Summary of Tables 9 through 13

Nominal Cement Factor	Round		Test Method* T1	T2	T3	T4	T5
4.5 sks.	1	$\overline{X}$**	452	473	214	235	241
		S	47	41	12	17	11
		V	10.4	8.7	5.6	7.2	4.6
	2	$\overline{X}$**	599	612	305	324	294
		S	26	56	34	27	15
		V	4.3	9.2	11.1	8.3	5.1
5.5-sks.	1	$\overline{X}$**	581	617	277	319	290
		S	58	53	45	33	24
		V	10.0	8.6	16.2	10.3	8.3
	2	$\overline{X}$**	658	666	324	348	329
		S	41	73	36	31	33
		V	6.2	11.0	11.1	8.9	10.0
6.5-sks.	1	$\overline{X}$**	718	829	365	432	395
		S	64	71	28	30	11
		V	8.9	8.6	7.7	6.9	2.9
	2	$\overline{X}$**	581	613	310	343	295
		S	54	33	37	22	21
		V	9.3	5.4	11.9	6.4	7.1
Average Coefficients of Variation for each test		V	8.4	8.8	11.2	8.1	6.8

*T_1 - Standard flexural test
T_2 - New beam breaker utilizing 20-inch beams, 18-inch span
T_3 - Tensile splitting test with hand-operated device, 6x6-inch specimens
T_4 - Tensile splitting test with hydraulic press; 6x6-inch specimens
T_5 - Tensile splitting test with hydraulic press; 6x12-inch specimens

** Each value is an average of 15 test specimens

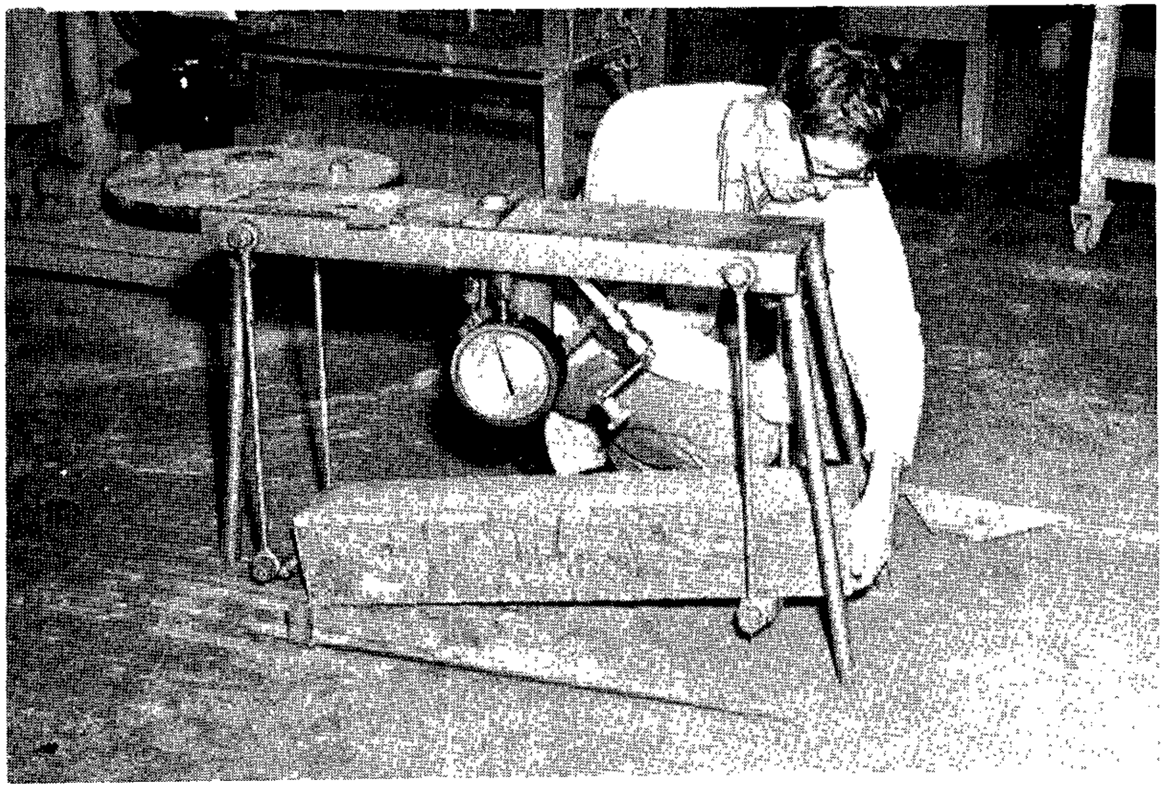

Figure 1.

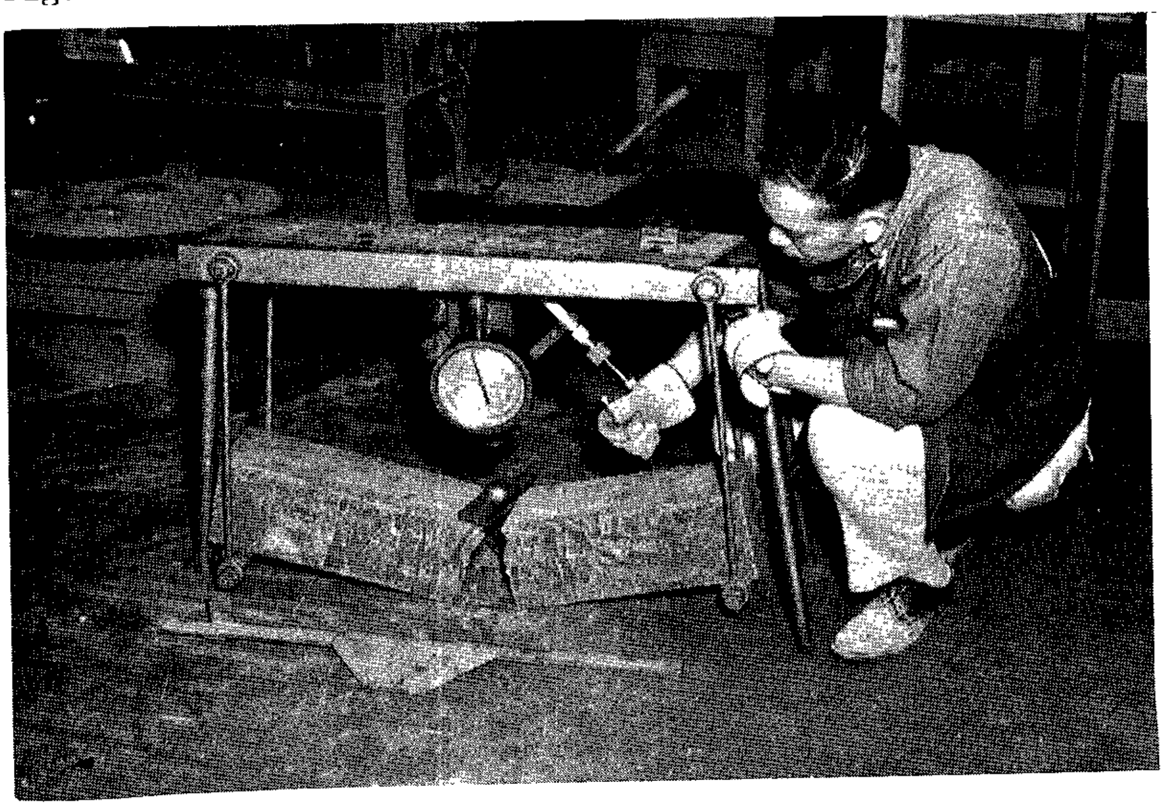

Figure 2. Testing 6x6x34-inch beam by present field methods

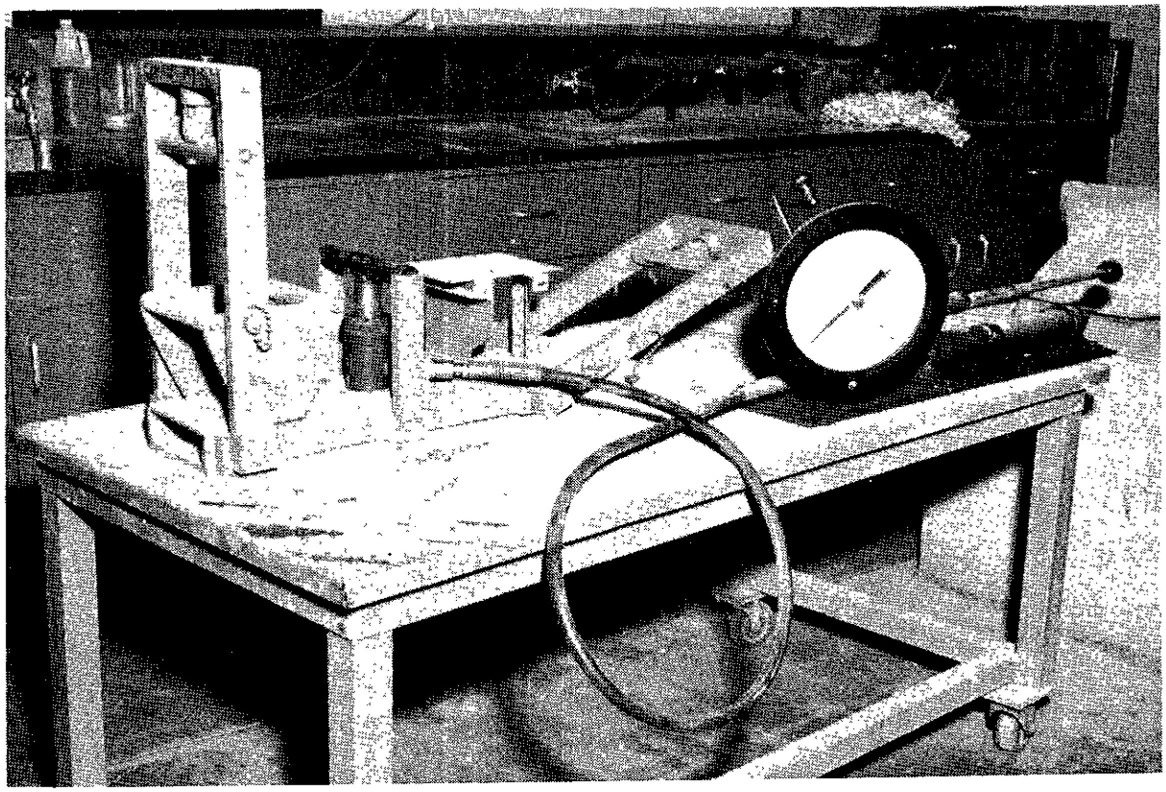

Figure 3.

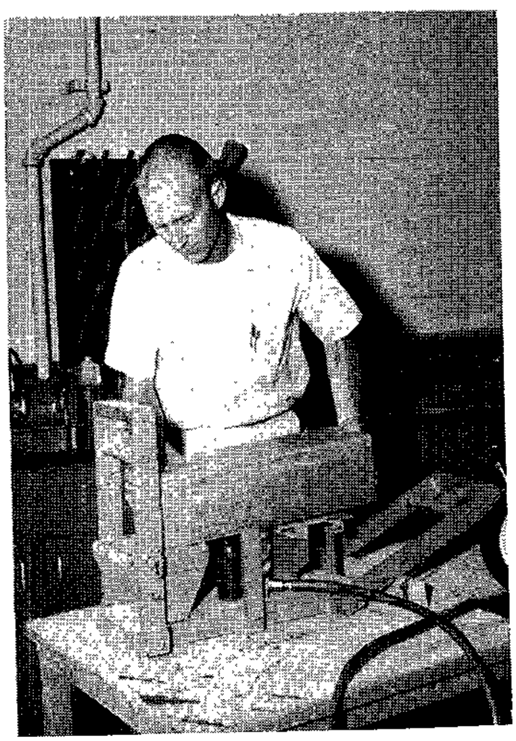

Figure 4.

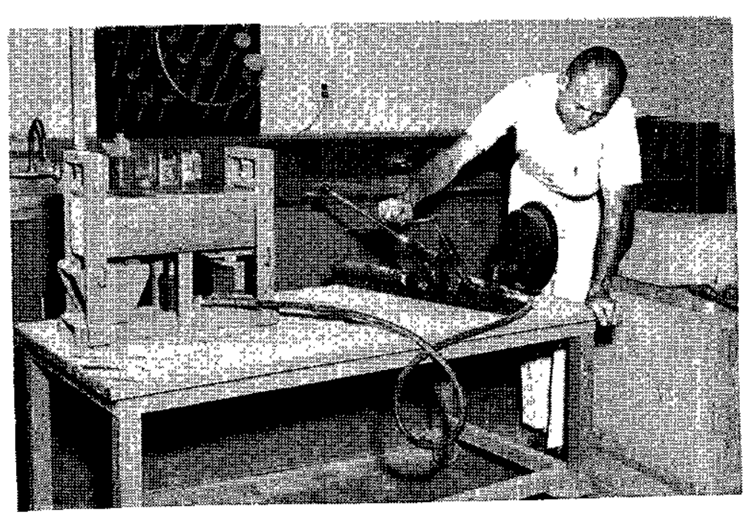

Figure 5.

Flexural test on 6x6x20-inch beams using new beam breaker.

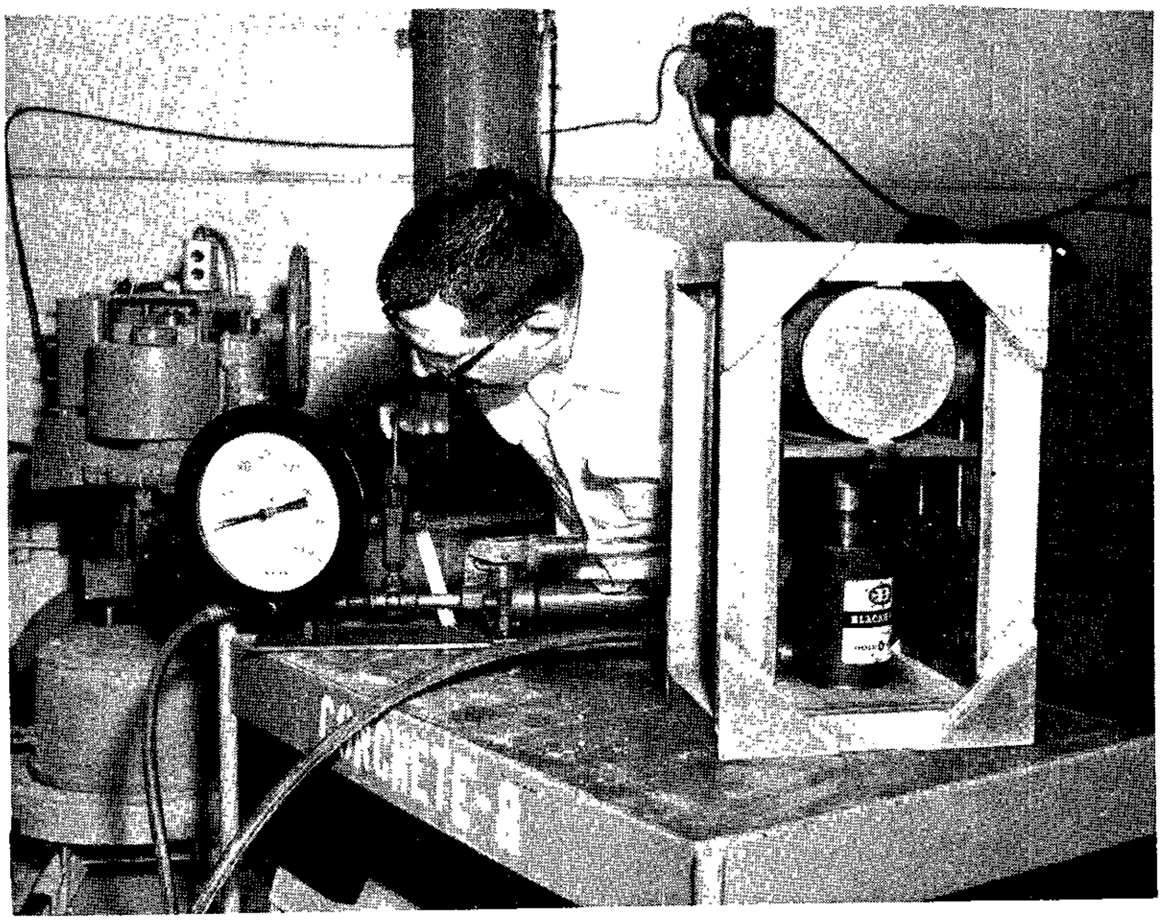

Figure 6.

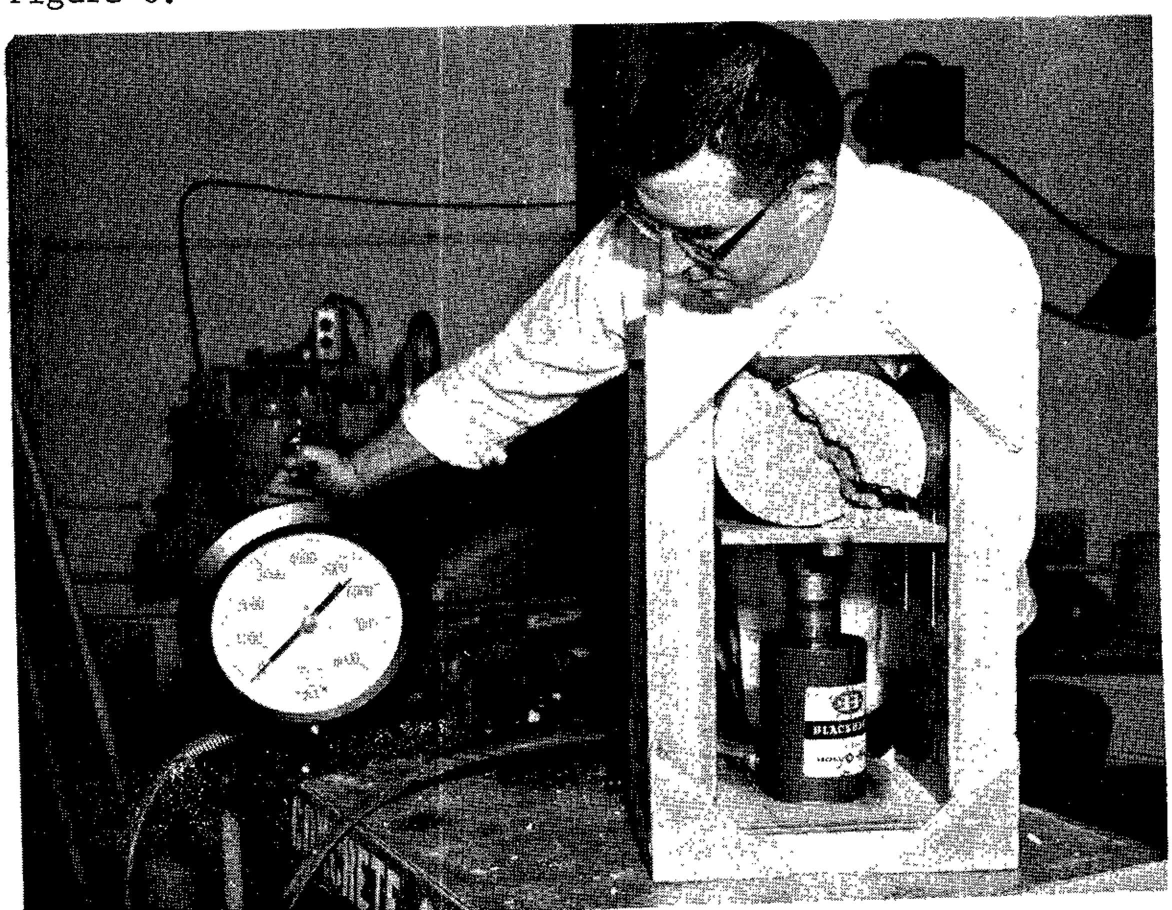

Figure 7. Tensile splitting test on 6x6-inch cylinder. (Hand-operated device.)

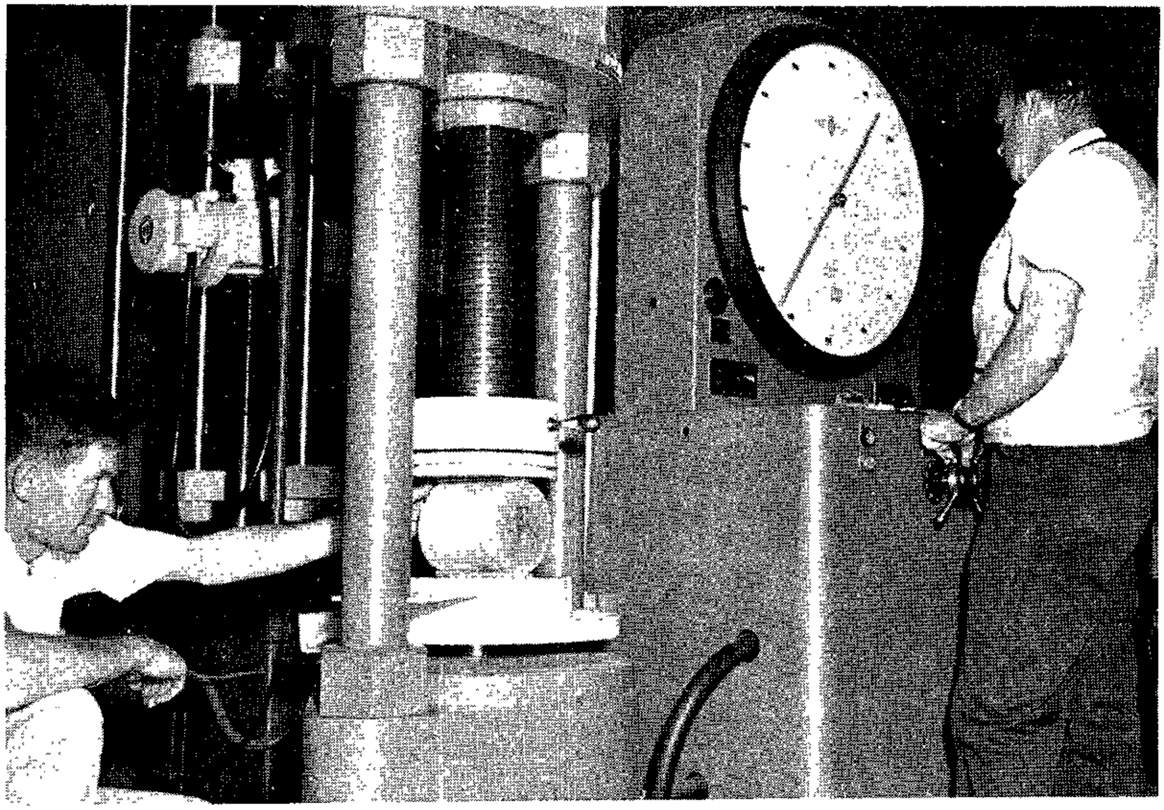

Figure 8. Tensile splitting test on 6x6-inch cylinder. (Hydraulic press.)

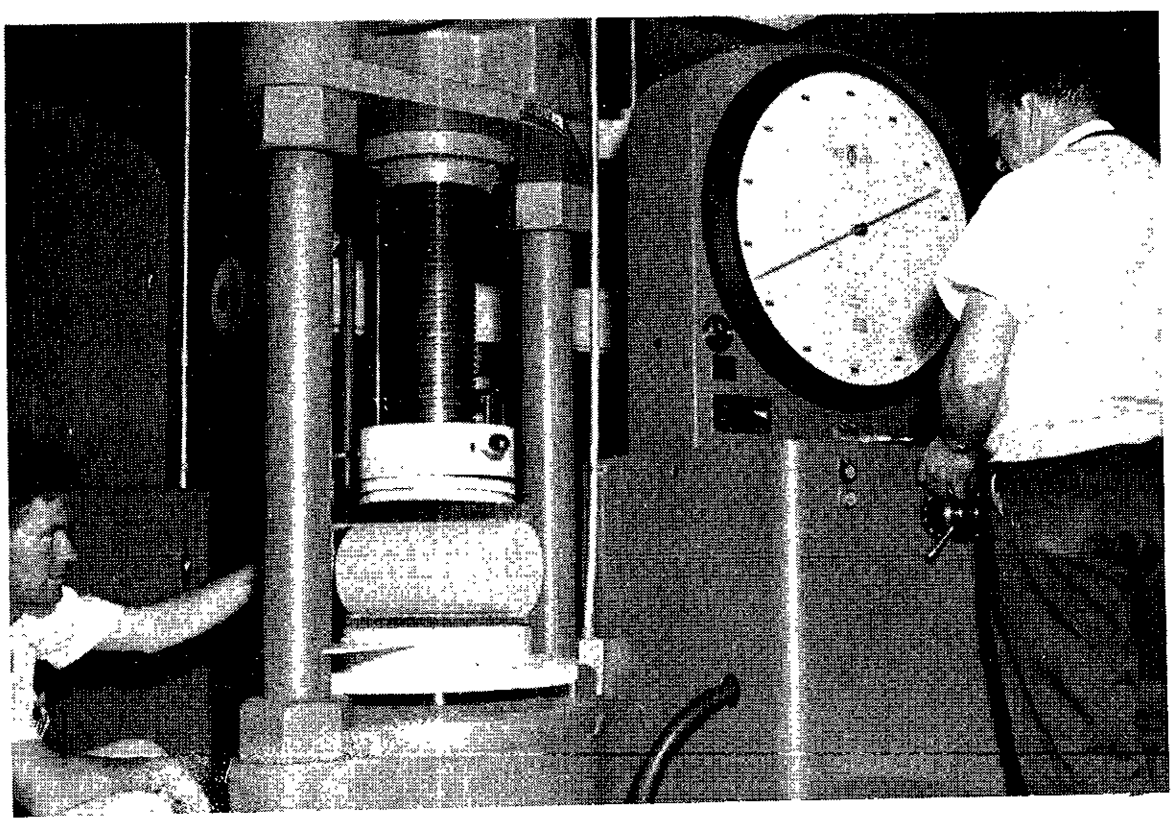

Figure 9. Tensile splitting test on 6x12-inch cylinder. (Hydraulic press.)